Performance of DSTM MIMO Systems Based on Weyl Group in Time Selective Channel

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***Abstract*—Traditionally, the channel used for differential multiple-input-multiple-output (MIMO) systems is constant during one frame and changes randomly from one frame to another. This channel behavior is too simple to be realistic. In this paper, we propose a new time selective channel model for differential space-time modulation (DSTM) schemes. A sufficient number of Rayleigh channel matrices are randomly generated, and the other channel matrices are sinc interpolated according to the Nyquist's sampling theorem. The performance of DSTM schemes with two, four and eight transmit antennas are evaluated over this time selective channel model. Simulation results show slightly degraded but more realistic performance when this new channel model is used.**

***Keywords*—MIMO, Differential Space-Time Modulation, non-coherent, channel model, Nyquist's sampling theorem, sinc interpolation.**

I. INTRODUCTION

Multiple-input-multiple-output (MIMO) technique has been widely analyzed in the last decade. This technique can enlarge the capacity and robustness of wireless communication systems and some of the schemes have been applied in current standards.

According to whether the receiver needs the channel state information (CSI), MIMO systems can be divided into two types. The type I that need CSI and the type II that do not need CSI. Type I systems are also called coherent MIMO systems. In [1], [2], the authors have analyzed the capacity and the error performance of such systems with Gaussian noise. As a consequence, several coding schemes have been proposed such as space-time block codes (STBC) [3], space-time trellis codes (STTC) [4], Bell Labs layered space-time codes (BLAST) [5], etc.

However, for the type I MIMO systems, the CSI is difficult to obtain when the number of antennas is large or the channel state changes rapidly. Indeed, the number of channel coefficients to be estimated by the receiver is equal to the product of the number of transmit antennas by the number of receive antennas. Furthermore, the length of the training sequences is proportional to the number of transmit antennas [6], which reduces the overall system throughput. When the channel state changes rapidly enough, the estimation of channel coefficients is even not achievable before they change to other values. Therefore, the type II MIMO systems that do not need CSI are attractive.

Generally, the type II MIMO systems often use differential schemes. For example, Tarokh and Jafarkhani proposed the differential space-time block coding (DSTBC) scheme [7] based on Alamouti's transmit diversity scheme [8]. Brian L. Hughes introduced a differential space-time modulation in [9]. Marzetta and Hochwald analyzed the capacity of the MIMO systems without CSI in [10] and designed the unitary space-time modulation (USTM) in [11]. Based on this scheme, Hochwald and Sweldens presented the differential unitary space-time modulation (DUSTM) scheme [12]. In [13], [14], we designed new differential schemes for MIMO systems based on the Weyl group.

However, the channel model used in [7], [9], [13], [14] is constant during one frame and changes randomly to a new one for the next frame, which is not realistic. The channel model of the papers [11], [12] is Jakes' model, which corresponds to wideband channels (frequency selective channels). In this paper, we propose a more realistic and easy to simulate time selective channel model. Then we evaluate the performance and the robustness of DSTM schemes with two, four and eight transmit antennas over this time selective channel.

The following notations will be used through the paper: $\mathrm{Tr}\{A\}$ denotes the trace of the matrix A and A^H means the conjugate transpose of A. $\|A\|$ is the Frobenius norm of A, i.e., $\|A\| = \sqrt{\sum_{i,j} |a_{ij}|^2} = \sqrt{\mathrm{Tr}\{A^H A\}}$. $\mathrm{Re}\{z\}$ is the real part of the complex number z. The zero-mean, unit-variance, circularly symmetric, complex Gaussian distribution is denoted as $CN(0,1)$.

II. DIFFERENTIAL MIMO SYSTEM MODEL

Generally, a MIMO system with M transmit antennas and N receive antennas can be written as:

$$y_{nt} = \sum_{m=1}^{M} h_{nm} x_{mt} + w_{nt}, n = 1, \ldots, N \qquad (1)$$

where x_{mt} is the symbol sent by the transmit antenna m at time t and y_{nt} is the symbol received by antenna n at time t; w_{nt} is the complex additive white Gaussian noise, $w_{nt} \sim CN(0, \sigma^2)$ and σ^2 is the noise variance. The coefficient h_{nm} is the path gain from the transmit antenna m to the receive antenna n. The coefficients h_{nm} are independent and identically distributed (iid), $h_{nm} \sim CN(0, 1)$. For a narrow-band MIMO channel, corresponding to low data rate wireless systems [15] or for each sub-channel of OFDM (Orthogonal Frequency Division Multiplexing) MIMO systems [16], the frequency response of the propagation channel can be considered constant within the frequency bandwidth of the system. Therefore, the coefficients h_{nm} of the channel matrix are usually considered constant over the frequency bandwidth but time-variant.

To analyze the MIMO system conveniently, the matrix form of the system is used:

$$Y_\tau = H_\tau X_\tau + W_\tau \tag{2}$$

where τ is the time index. X_τ is the $M \times T$ transmission matrix, where T denotes the number of symbols transmitted by each antenna during the transmission of one matrix X_τ. H_τ is the $N \times M$ channel matrix at time τ . W_τ is the $N \times T$ complex, additive white Gaussian noise matrix and Y_τ is the $N \times T$ received matrix.

We define L equal to the normalized coherence time T_c/T_s during which the channel matrix H_τ is approximately constant, where T_c is the coherence interval and T_s is the symbol duration. A popular definition of T_c is: $T_c = \sqrt{\frac{9}{16\pi f_d^2}} = \frac{0.423}{f_d}$ [17], where $f_d = \frac{v}{\lambda}$ is the Doppler spread, v is the relative velocity between the transmitter and receiver, and λ is the signal wavelength. In practice, for simplicity, people usually use it as $T_c \approx 0.5/f_d$. For example, with velocity $v = 120$ km/h, and carrier frequency $f = 900$ MHz, the Doppler spread is approximately 100 Hz and the coherence interval is approximately 5 ms. For a symbol rate of 30 kHz, $L = 150$ symbols are transmitted during the coherence interval T_c. For high speed vehicular $v = 350$ km/h channels [18], and carrier frequency $f = 2.5$ GHz, the Doppler spread is approximately 810 Hz and the coherence interval is approximately 0.6 ms. For a symbol rate of 500 kHz, $L = 300$ symbols are transmitted during this coherence interval.

For convenience, at each time slot the total power over M transmit antennas is set to be 1:

$$\sum_{m=1}^{M} |x_{mt}|^2 = 1, t = 1, \ldots, T. \tag{3}$$

It is proved in [10] that for non-coherent MIMO systems, the capacities obtained with $M > T$ and $M = T$ are equal. Therefore, we choose $M = T$ in our study.

The SNR is defined as follows:

$$\begin{aligned} SNR &= \frac{E[|y_{nt} - w_{nt}|^2]}{E[|w_{nt}|^2]} = \frac{E\left[|\sum\limits_{m=1}^{M} h_{nm}x_{mt}|^2\right]}{E\left[|w_{nt}|^2\right]} \\ &= \frac{E\left[\sum\limits_{m=1}^{M} |h_{nm}x_{mt}|^2\right]}{\sigma^2} = \frac{E\left[\sum\limits_{m=1}^{M} |x_{mt}|^2\right]}{\sigma^2} = \frac{1}{\sigma^2} \end{aligned} \tag{4}$$

where $E[\cdot]$ denotes the mathematical expectation.

A. The model of differential space-time modulation

For differential space-time modulation systems, the information matrix is used to multiply the previous transmitted matrix. In general, the information matrix is selected from a group P according to the incoming information bits. For example, at time τ, X_τ is transmitted. At the next time $\tau + 1$, a block of information bits is mapped onto the matrix $V_{i_{\tau+1}}$ from the group P, and then the matrix

$$X_{\tau+1} = X_\tau V_{i_{\tau+1}} \tag{5}$$

is transmitted. This relation is the fundamental differential transmission equation.

Therefore, the sequence of transmitted matrices is:

$$\begin{aligned} &X_0 = V_0 \\ &X_1 = X_0 V_{i_1} = V_0 V_{i_1} \\ &X_2 = X_1 V_{i_2} = V_0 V_{i_1} V_{i_2} \\ &\ldots \\ &X_\tau = X_{\tau-1} V_{i_\tau} = V_0 V_{i_1} \ldots V_{i_\tau} \\ &\ldots \end{aligned}$$

In general, the reference matrix V_0 is the identity matrix. To satisfy the constraint (3) imposed on the total transmit power, all the matrices of the group P should be unitary matrices.

Furthermore, a perfect synchronization is assumed. Subsequently, a matrix stream $Y_0, \ldots, Y_\tau, Y_{\tau+1}, \ldots$ is detected by the receive antennas, according to

$$Y_\tau = H_\tau X_\tau + W_\tau \tag{6}$$

and

$$Y_{\tau+1} = H_{\tau+1} X_{\tau+1} + W_{\tau+1} \tag{7}$$

For a quasi-static channel during the transmission of two successive matrices X_τ and $X_{\tau+1}$, we have the assumption:

$$H_{\tau+1} \approx H_\tau \tag{8}$$

Using the differential transmission equation (5), we get

$$\begin{aligned} Y_{\tau+1} &= H_{\tau+1} X_{\tau+1} + W_{\tau+1} \\ &\approx H_\tau X_{\tau+1} + W_{\tau+1} \\ &= Y_\tau V_{i_{\tau+1}} + W'_{\tau+1} \end{aligned} \tag{9}$$

where $W'_{\tau+1} = W_{\tau+1} - W_\tau V_{i_{\tau+1}}$.

As Y_τ and $Y_{\tau+1}$ are known by the receiver, we can use the maximum likelihood detector to estimate the information matrix:

$$\begin{aligned} \hat{V}_{i_{\tau+1}} &= \arg\min_{V \in P} \|Y_{\tau+1} - Y_\tau V\| \\ &= \arg\min_{V \in P} \mathrm{Tr}\{(Y_{\tau+1} - Y_\tau V)^H (Y_{\tau+1} - Y_\tau V)\} \\ &= \arg\max_{V \in P} \mathrm{Tr}\{\mathrm{Re}(Y_{\tau+1}^H Y_\tau V)\} \end{aligned} \tag{10}$$

The detector gives good results if (8) is verified, i.e., the propagation channel can be considered quasi-static during the transmission of two successive matrices X_τ, $X_{\tau+1}$. The propagation channel proposed in this paper allows some variation of the propagation channel and investigate the performance degradation of the DSTM MIMO systems compared to their performance obtained considering the channel matrix constant during a frame.

III. The New Improved Channel Model

A. The usual channel model for differential MIMO systems

As mentioned before, the channel model used in [7], [13], [14] is constant during one frame and changes randomly for the next frame. For example with the normalized coherence interval $L = 200$, for M transmit antennas and N receive antennas, during the transmission of the first 200 symbols, the same channel matrix H_τ is considered. The next channel matrix $H_{\tau+1}$ is randomly generated to be used for the next 200 symbols. However, this is not the real case. In reality, the channel changes continuously. Furthermore, at the beginning of the new frame, the reference matrix V_0 has to be transmitted again. This reduces the overall simulation efficiency.

B. The new improved channel model

To overcome the fault of channel model mentioned in last subsection, we propose a new channel model which changes continuously.

With M transmit antennas and N receive antennas, during the coherence interval L, $N_m = L/T = L/M$ transmit matrices will be sent. Thus N_m channel matrices are needed to multiply the transmit matrices. We interpolate $N_m - 1$ channel matrices $H(1), \ldots, H(N_m - 1)$ between two successive randomly generated channel matrices R_K and R_{K+1} instead of one constant channel matrix R_K. The $N_m - 1$ interpolated channel matrices are related to the passed channel matrices and also to the future channel matrices.

The interpolated channel sequence $H(1)$, $H(2)$, $\ldots$, $H(N_m - 1)$ is generated as follows:

1) A fix number $2K$ of Rayleigh distributed matrices are randomly generated, i.e., $R_1, \ldots, R_K, R_{K+1}, \ldots, R_{2K}$.
2) With the Nyquist's sampling theorem, the channel sequence between R_K and R_{K+1} is generated by sinc interpolation.

Using the well-known Nyquist's sampling theorem, a band-limited signal $x(t)$ can be reconstructed from its samples $x(kT_0)$ as follows:

$$\begin{aligned} x(t) &= \sum_{k=-\infty}^{+\infty} x(kT_0) \frac{\sin f_0 \pi (t - kT_0)}{f_0 \pi (t - kT_0)} \\ &= \sum_{k=-\infty}^{+\infty} x(kT_0) \frac{\sin \pi (f_0 t - k)}{\pi (f_0 t - k)} \end{aligned} \tag{11}$$

if the sampling frequency $f_0 = 1/T_0 > 2f_M$, where f_M is the maximum frequency of the signal. In our case, the Rayleigh random matrices R_k can be considered as samples of the continuous channel matrix H separated by the coherence interval, so $T_0 = T_c = LT_s$. With $2K$ randomly generated matrices, we get the $N_m - 1$ interpolated channel matrices between the matrices R_K and R_{K+1}:

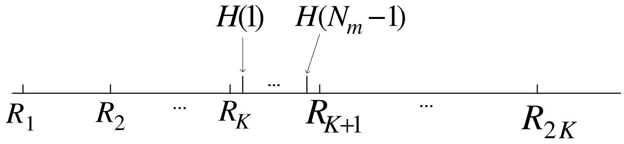

Fig. 1. Illustration of the interpolation of the channel matrix H.

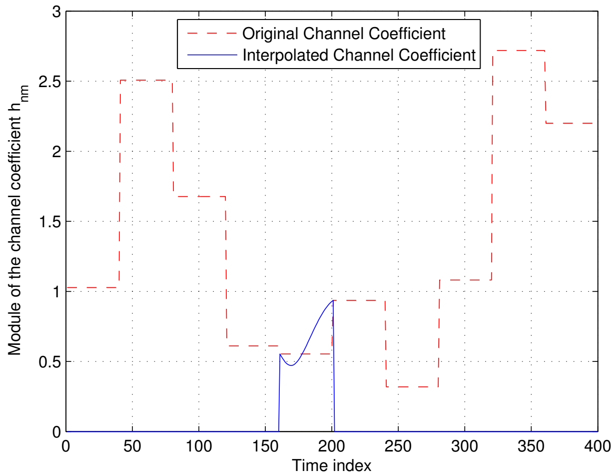

Fig. 2. Comparison of the two channel models considering one channel coefficient h_{nm}, interpolated by the passed and future random variables.

$$\begin{aligned} H(i) &= \sum_{k=1}^{2K} R_k \frac{\sin \pi \left[f_0 (KLT_s + iMT_s) - k \right]}{\pi \left[f_0 (KLT_s + iMT_s) - k \right]} \\ &= \sum_{k=1}^{2K} R_k \frac{\sin \pi (K + i/N_m - k)}{\pi (K + i/N_m - k)}, \\ & i = 1, 2, \ldots, N_m - 1. \end{aligned} \tag{12}$$

For example, with $2K = 10$ randomly generated Rayleigh channel matrices R_1, $\ldots$, R_5, R_6, $\ldots$, R_{10}, the number of transmit antennas $M = 4$, and the normalized coherence interval $L = 160$, we get $N_m - 1 = 39$ interpolated channel matrices $H(i)$ between R_5 and R_6. This procedure is illustrated in Fig 1.

The module of one channel coefficient h_{nm} obtained by interpolation between R_K and $R_{K+1}$is shown in Fig. 2. A complete figure of the generated channel coefficient h_{nm} compared with the randomly generated Rayleigh values is given in Fig. 3.

We can see that the channel generated by this method changes slightly for each two successive transmit matrices.

However, there is still the problem of the selection of the number K. Here, we resort to the relative error to select appropriate K. As discussed before, with $2 \times K$ Rayleigh distributed channel matrices, we get $N_m - 1$ interpolated channel matrices. We select a very large number, for example $K_{max} = 4000$ to get a group of interpolated reference channel matrices. We estimate that K_max is large enough to obtain

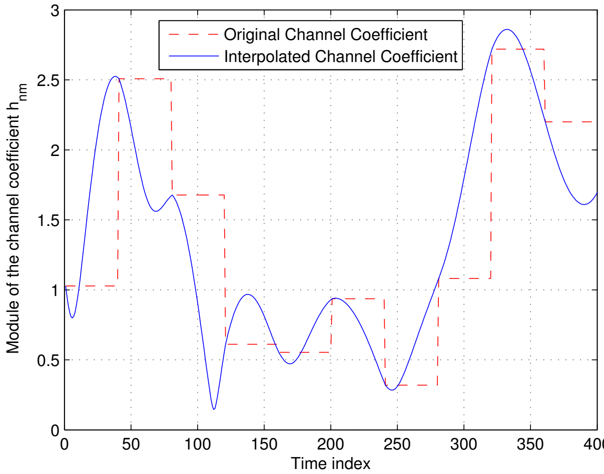

Fig. 3. Time variation of the module of one channel coefficient h_{nm}.

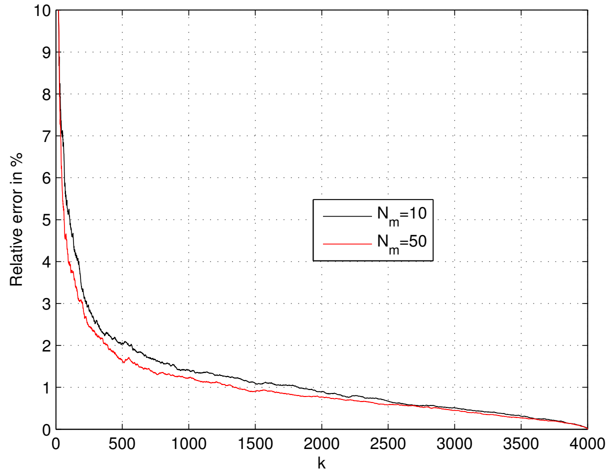

Fig. 4. The relative error versus different numbers of k with $N_m = 10$ and $N_m = 50$ respectively.

accurate channel matrices by interpolation. With K decreasing to 1, we get other $K_{max} - 1$ groups of interpolated channel matrices. Compared with the reference group, each group has different variations. The groups of interpolated channel matrices are:

$$\{H^k(1), H^k(2), \cdots, H^k(N_m - 1)\}, k = 1, \cdots, K_{max}. \quad (13)$$

We define the mean relative error as:

$$\varepsilon_k = \frac{1}{N_m - 1} \sum_{i=1}^{N_m - 1} \frac{\|H^{K_{max}}(N_m) - H^k(i)\|}{\|H^{K_{max}}(i)\|}, \quad k = 1, 2, \cdots, K_{max}. \quad (14)$$

As the matrices $R_1, \ldots, R_K, R_{K+1}, \ldots, R_{2K}$ are generated randomly, the curve of the relative error is very rough. To smooth the curve, we calculate the relative error 100 times and get the mean as the final relative error. The curve of relative error is shown in Fig. 4 with $K_{max} = 4000$ and $N_m = 50$. We get the table of relative error versus K in Table I with $N_m = 50$ and $N_m = 10$ respectively. On the basis of these data, we set $K = 30$ in our simulations. In this case, the relative error is below 10%.

$N_m = 50$		$N_m = 10$	
Relative error	K	Relative error	K
2%	389	2%	548
3%	201	3%	229
5%	62	5%	105
9.725%	22	9.678%	21
10.23%	21	10.18%	20

TABLE I
THE VALUES OF K FOR DIFFERENT RELATIVE ERRORS WITH $K_{max} = 4000$.

IV. The Differential Space-time Modulation Scheme

In this paper, the performance of the DSTM schemes proposed in [13], [14] are evaluated over this new channel model. This scheme is based on the Weyl group.

The multiplicative Weyl group G_w [19] is generated by two matrices $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$ and $\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$. As these two matrices are unitary, all the matrices generated by them are also unitary. For convenience, we divide the group into 12 cosets $(C_0, C_1, \ldots, C_{11})$. Each coset contains 16 invertible matrices. The first coset which is also a subgroup of the Weyl group is defined as:

$$C_0 = \alpha \left\{ \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}, \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}, \begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix} \right\} \quad (15)$$

with $\alpha \in \{1, -1, i, -i\}$. The 12 cosets of G_w are derived from C_0 as follows:

$$C_k = A_k C_0, \forall k = 0, 1, \ldots, 11 \quad (16)$$

where the matrices $A_k, k = 0, 1, \ldots, 5$ are respectively:

$$A_0 = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, A_1 = \begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}, A_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix},$$
$$A_3 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ i & -i\end{bmatrix}, A_4 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ 1 & -i\end{bmatrix}, A_5 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix},$$

and the matrices $A_k, k = 6, 7, \ldots, 11$ are given by:

$$A_{k+6} = \eta A_k, with \quad \eta = (1 + i)/\sqrt{2}, \forall k = 0, 1, \ldots, 5 \quad (17)$$

We define the distance between two matrices M_a and M_b as:

$$D(M_a, M_b) = \|M_a - M_b\|. \quad (18)$$

A. DSTM scheme with 2 transmit antennas

In this paper, for MIMO systems with 2 transmit antennas and $R = 1$ bps/Hz, 4 matrices are needed. We select matrices $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$, and $\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$ as the information group. For $R = 2$ bps/Hz, we select C_0 which has 16 matrices as the group to map the 4 bits information block as in [13].

B. DSTM scheme with 4 transmit antennas

For MIMO systems with 4 transmit antennas, the *Kronecker product* is used to expand the 2×2 Weyl group to a 4×4 matrices group. In fact, there are 4608 distinct matrices in this group G_{w4}.

For $R = 1$ bps/Hz, the first matrix in C_0 ($\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$) is used to make Kronecker product with all the matrices in C_0 to get 16 unitary matrices as in [14].

For $R = 2$ bps/Hz, the best set used in [14] which contains 256 matrices is used here. In fact, the first 16 matrices from every successive 192 matrices of the group G_{w4} are selected to form the set.

C. DSTM scheme with 8 transmit antennas

For MIMO systems with 8 transmit antennas and $R = 1$ bps/Hz, 256 matrices should be generated as the mapping group. We get the group as follows. First, we generate a set of 16 matrices of C_{44} by using the Kronecker product between the first 4 matrices of C_0. Second, the Kronecker product between C_0 (16 matrices of the size 2×2) and C_{44} (16 matrices of the size 4×4) produces a set C_{88} with 256 matrices.

V. Simulation Results

The performance of the differential MIMO systems are evaluated over the frame constant channel (step channel) and over the proposed time selective channel (continuous channel). We set $L = 200$, which means that for 2, 4 and 8 transmit antennas, $N_m = 100, 50$ and 25 respectively.

Fig. 5 shows that for $R = 1$ bps/Hz, the M8N8 scheme offers for BER = 10^{-4} a SNR gain of about 5.5 dB compared to the M4N4 scheme and 17 dB compared to the M2N2 scheme on the step channel. Over the new continuous channel, similar gains are obtained with the M8N8 scheme compared to the M4N4 and M2N2 schemes. Furthermore, using the continuous channel leads to a degradation compared to the step channel which is about 1 dB for a BER = 10^{-4} with the M8N8 scheme and 0.6 dB with M2N2 scheme. Similar relative results for $R = 2$ bps/Hz M8N8, M4N4 and M2N2 schemes are obtained in Fig. 6. As expected, the M8N8 scheme is more sensitive than the M4N4 and M2N2 schemes to the time selectivity of the channel.

Fig. 7 presents the performance of M4N4 DSTM scheme with $R = 1$ bps/Hz over the step channel and over the new continuous channel with different normalized coherence time L. As already mentioned, the faster the channel changes, the smaller the value of L. Consistent with our supposition, there is a trend that as L grows the BER performance becomes better.

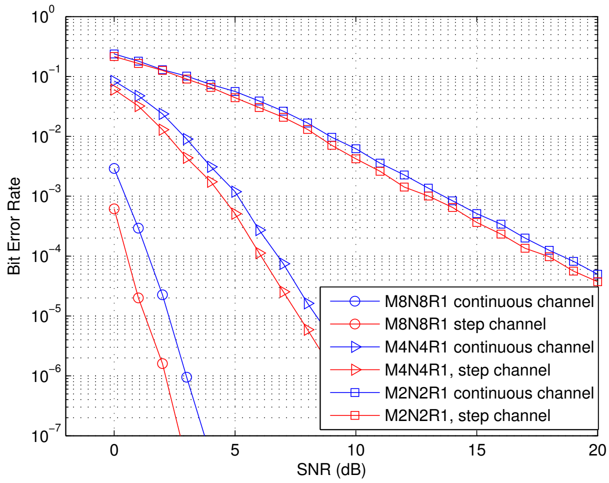

Fig. 5. Performances of differential space-time schemes with $R = 1$ bps/Hz over different channel models.

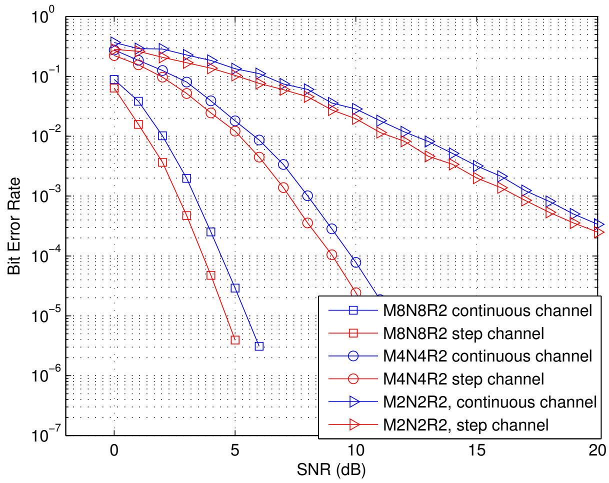

Fig. 6. Performances of differential space-time schemes with $R = 2$ bps/Hz over different channel models.

VI. Conclusion

In this paper we propose a simple and more realistic time-selective propagation channel in order to obtain more reliable estimations of the performance of DSTM MIMO systems with 2, 4 and 8 transmit antennas. This model is based as usual on random Rayleigh channel matrices but is completed with intermediate channel matrices obtained by sinc-interpolation. During the transmission of two successive matrices, the propagation channel may change, which determines a degradation of the performance of the differential system. This degradation is evaluated by simulation for DSTM MIMO systems using 2, 4 and 8 transmit antennas and for two values of the spectral efficiency. As expected, the degradation is more important for MIMO systems using more antennas. Moreover, the degradation is more important if the normalized coherence time is reduced. Thus, the proposed channel model does not make

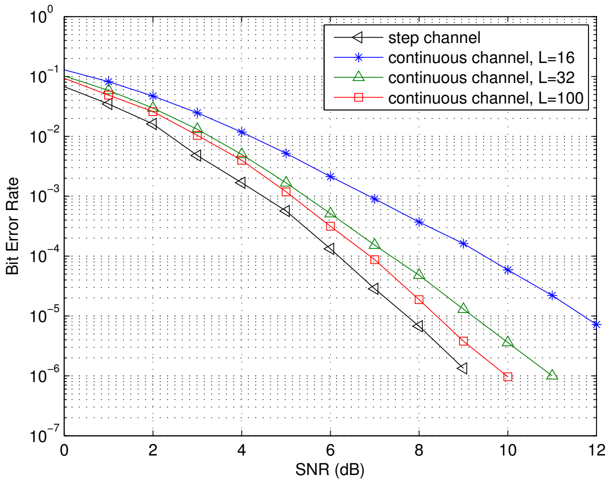

Fig. 7. Performance of the DSTM M4N4R1 scheme with different L.

a difference between slow and fast Rayleigh channels, the only parameter making the difference being the normalized coherence time.

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